Renewable and Sustainable Energy Reviews 15 (2011) 648–656

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Maximization of wind energy penetration with the use of H_2 production—An exergy approach

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ARTICLE INFO

Article history:
Received 15 December 2009
Accepted 23 June 2010

Keywords:
Renewable energy
Wind energy
Hydrogen
Exergy analysis

ABSTRACT

The utilization of wind energy has been the outmost energy objective of many countries in the EU in the past two decades. The low value of its reliability factor constitutes the biggest drawback for its use. The instability of wind speeds may lead to over-production of electricity from wind power generators at one time, and lack of production to satisfy demand at others. An energy carrier such as hydrogen would play a significant role in increasing the reliability of wind power generation systems.

There are two objectives of this work; the first one is to investigate the possibility that hydrogen could be technically and economically produced by wind energy, according to up-to-now scientific research, in order to increase the wind energy penetration percentage in weak electric systems. A concise description of problems that result from wind integration in the systems of high wind penetration is enterprised, also referring to the existing solution suggestions, one of which is the production of hydrogen. The role of hydrogen in high wind penetration systems is described as well, and finally, a preliminary techno-economical case study of an electrolysis unit installation in an existing wind park in Crete island is also presented.

The second objective is to examine and analyse thermodynamically, the efficiency along the hydrogen and electricity production cycle, starting from the kinetic energy of the wind. The change of exergy due to losses at different points is being mapped and mathematically calculated. It is shown that there is a two fold change in exergetic efficiency along both paths. The same case study of the wind farm is taken as a system for examination.

All the data used in this work come from Greece, specifically the island of Crete.

Contents

1. Introduction

On account of the wide interest that was expressed for windfarms (W/F) installation by the beginnings of 1990s, world wind energy installed capacity nowadays reaches 40,000 MW, 28,000 MW of which are in Europe, whereas in Greece there are more than 400 MW [1]. One of the main problems, however, which

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1364-0321/$ – see front matter © 2010 Published by Elsevier Ltd.
doi:10.1016/j.rser.2010.06.022

contributed in the delay of W/F installation, was the fact that wind power integration in electric grids has important consequences in its operation and requires major investments. It should also be mentioned that another setback for the further development of renewable energy sources (RES) in Greece, is the fact that investors who intend to issue installation and operation licenses meet time-consuming and laborious procedures. Nevertheless, the prospect of important wind energy penetration in the energy balance is already visible, considering the major investors' interest on one hand, and the political will for further RES integration on the other hand.

Hydrogen, in combination with electricity, is widely recognized as one of the future most outstanding energy carriers, while it will also be a contributing factor to the further integration of wind energy within the electricity distribution grid. It represents an ideal means of storage of surplus RES energy via electrolysis in combination with fuel cells, used for its re-electrification. Sufficient storage capacity will allow the seasonal energy storage, which is most suitable for the autonomous networks, like the case of islands. Hydrogen, produced in this way, can be used as a substitute of conventional liquid fuels, in heating and transportation purposes.

2. Windparks operation in electric grids

As already mentioned, windparks (W/P) connection and parallel operation in electric systems (ES) can present unfavourable consequences to its consumers, i.e. stability and continuity of grid supplied tendency. Distributed energy production (DEP) effects ES operation in two levels [2]:

(A) At the local distribution and transmission network, when "power quality" (tendency and frequency) supplied to consumers is affected. The disturbances can be distinguished in two levels [3]:
  (1) those which take place during network's regular operation and are basically made up of tendency disturbances, and
  (2) those which take place during network's abnormalities (short-circuits)
(B) In the production and the value of produced wind energy, when DEP exceeds the limit of 10% of total installed power.

- *Generation capacity value*. Although wind energy may have a certain capacity allowance, its unreliability requires the system to keep reserve capacity, especially at high penetration levels as the partial loss of generation from the wind becomes an increasingly significant source of risk of demand exceeding available generation.
- *Transmission and local network value.* The fact that good wind sites are often located remotely from electric loads in weak parts of the grid heightens the required investments, whose impact on the wind energy cost is worsened by the low capacity factor.

There are many ways to overcome these obstacles [3]:

In small autonomous systems (1000 KW), where the conventional production consists of one or more diesel-generators, energy storage modules can be used in order to increase wind energy penetration up to 100% of maximum demand (island of Kythnos, Greece). *In larger autonomous systems* (up to 40 MW), where the conventional production also consists of diesel-generators, energy storage is practically feasible only under certain circumstances and can be obtained only by pump storage units [4] or with fuel cells (in medium term), when there is surplus of produced wind power.

In large-national ES, usually interconnected with neighbouring countries, and in case of *large islands*, where energy production comes from several plants, high technology progress in data processing and transfer allows the continuous observation of ES operation. The effective, premium and safe daily operation of ES depends on the operation Energy Control Centres (ECC), which are responsible for all processes that contribute electrical grids.

Short-term wind forecasting is envisaged as a key tool for improving the management of the reserve capacity and lessening this loss of value. *Geographical dispersion* is also acknowledged as an important means to achieve smooth and less unpredictable combined output of wind farms located on distant sites. Although both will contribute to overall system efficiency and facilitate increased wind capacity, their impact is limited, especially as the wind penetration level increases [2].

The generation of hydrogen from excess wind-generated electricity absorbs the quantity of energy that is not absorbed by the network and additionally offsets the drop of wind energy value at high penetration levels in the following ways [2]:

- It smoothes the power output and hence facilitates a more efficient operation of the electric system. The smaller scale of the fluctuations reduces the need for ancillary services to maintain power quality.
- It helps avoiding wind plant shedding. The substantial production loss, in Ireland for instance foreseen by the study cited below, stresses the potential of hydrogen generation.
- It contributes in reducing the scale of the necessary grid reinforcements if hydrogen generation plants are installed in areas with a high wind power concentration.

3. Hydrogen production by wind energy

During recent years, significant experience in renewable hydrogen facilities operation has been achieved. Several research projects (like RES2H2), usually small-scale plants, have contributed to improving the integration of the various components, testing new developments and identifying weak points. Installations like these have already passed through the phase of testing and demonstration and have been brought into operation, in experimental stage, and in most of cases important and optimistic conclusions have been reached.

The general layout of a wind-hydrogen system is represented in Fig. 1 [5]. When the power generated by wind farms exceeds the regional or scheduled demand, the surplus is used to electrolyse water. The hydrogen produced and stored can be either used for transport or supplied to stationary fuel cells in order to generate power again when required.

Surplus wind energy exploitation, which will be heavily influenced by political decisions, can play a key part in the abatement of harmful emissions. In Greece, transportation sector was responsible for 23% of the total CO_2 emissions in 1999, whereas future estimations are especially discouraging. It is estimated that these emissions will take an increase of 81% during 1990–2010, unless dynamic meters for the decrease of the travelled kilometres are undertaken. Table 1 [2] shows the number of vehicles that could be fuelled with hydrogen produced from the growing surplus electricity that results from gradually adding new wind capacity and limiting the instantaneous wind power to 30% of total generation.

A similar plant study has been developed in case of Ireland [2]. Ireland is richly endowed with renewable energy resources, whereas it is the second most energy import-dependent country in Europe (87% of the energy needs in 2001), and it is also committed to a maximum increase of 13% in CO_2 emissions by the Kyoto Protocol. At present, wind power development in Ireland remains modest, with an installed power representing only 2.4% of a total generation capacity approaching 5000 MW, contributing to about 1.5% of the electricity demand.

In this case study of County Cork, Ireland, four wind farms supply their aggregated power to a portfolio of regional customers.

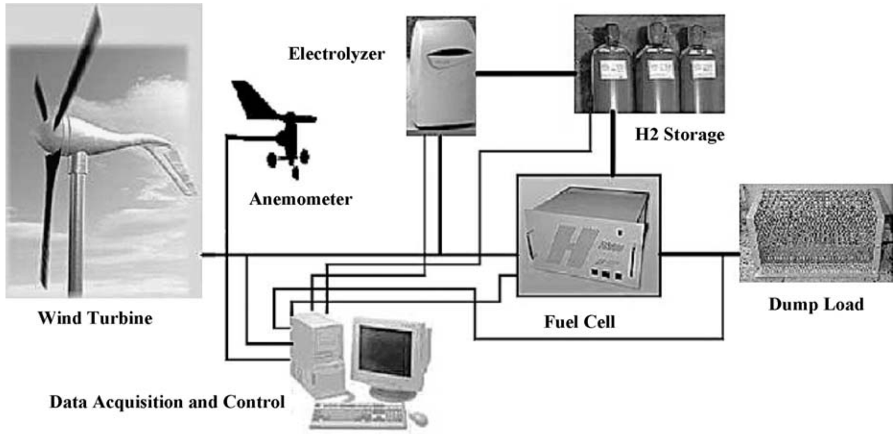

Fig. 1. Flowchart of a wind fuel cell hybrid energy system.

An electrolysis facility connected to the grid on a site near the wind farms absorbs most of the surplus electricity exceeding the regional customers' demand. The overall installed capacity of the four wind farms is 100 MW, yielding 379.5 GWh/a. In the case study analysed, the total regional demand of the customers' amounts to 322.6 GWh/a (85% of the wind farms' yield). This demand reaches an annual peak of 57.9 MW and a minimum of 20.2 MW. The power output surpasses the demand of 4473 h a year, the total surplus energy amounting to 135.9 GWh (35.8% of the total). The power output and the demand for a particular seven-day period is shown in Fig. 2.

A similar study, alike the case of Ireland, could possibly approach the insular ES of Crete, in southern Greece.

4. The electricity system of Crete, Greece

Crete's electrification system, with an installed power of about 730 MW, consists mainly of conventional diesel power stations. It also includes two hydro-power stations, with a capacity of 760 kW, and a significant number of W/Fs, reaching 57.3 MW at the end of 1999, and 80 MW at the end of 2003. Wind energy contributes already more than 10% to Crete's energy balance (Fig. 3) [6].

The system taken as a case study refers to IWECO MV W/F, which lies in central Heraklion prefecture, in Crete island (Fig. 4), and it is a fully operational power facility by the beginings of 1999. It consists of 9 Zond Z43 wind turbines, each of which is capable of producing 550 kW of electrical power and thus the whole facility capacity is 4.95 MW. The annual production energy of the windfarm is able to meet the demand in electricity of about 5000 residents of Crete.

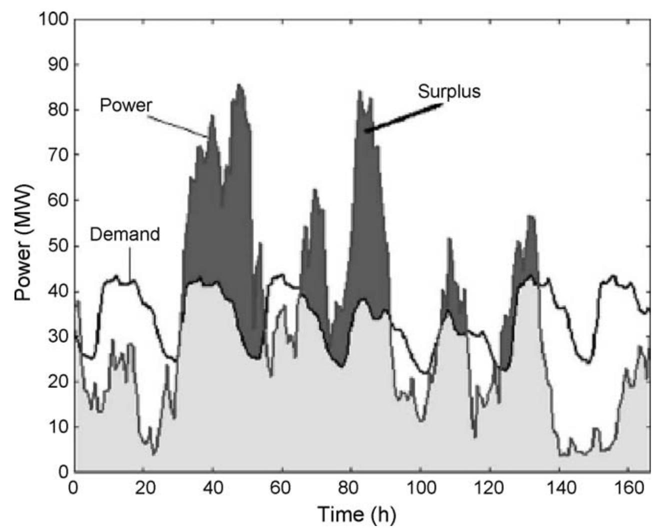

Fig. 2. Power output and load for seven days at County Cork (Ireland).

Considering that Crete constitutes an autonomous electrical system, W/F installation limit is constrained by Greek laws (2294/94) [1], to 30% of previous year peak load. Wind energy penetration percentage during operation is kept low, because of dynamic impacts, disturbances, and technical minimum levels of production of conventional energy units which limit the total possible absorbed wind power. Greek Public Power Corporation (PPC) annually defines the minimum number of hours, at which W/Fs' produced power

Table 1
Cars fuelled and CO_2 avoided emissions at different wind capacities.

Installed wind capacity (MW)	Car fleet fuelled	Avoided CO_2 car emissions (kTn)
0	0	0
700	0	0
750	15	0.05
800	56	0.18
900	334	1.04
1000	1103	3.45
1200	5055	15.8
1500	19,749	61.7
2000	68,801	215
2500	135,160	423
3000	209,580	655
3500	288,681	903
4000	370,953	1160
4500	455,338	1424
5000	541,422	1693

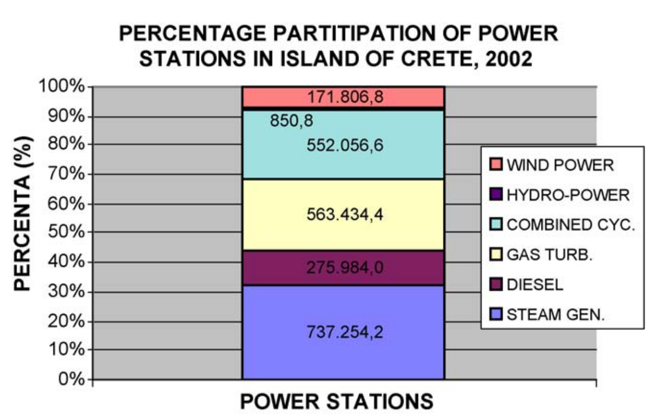

Fig. 3. Percentage participation of power stations in Crete's energy balance, in 2002.

Fig. 4. RES development in Crete (2000). The studied W/F can be distinguished.

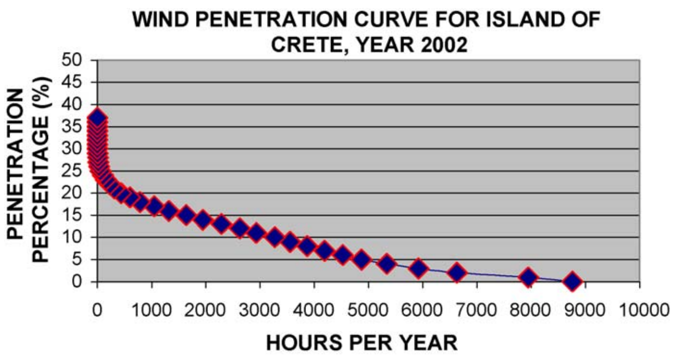

Fig. 5. Wind energy penetration curve of Crete's ES.

Table 2
Monthly averages of produced energy, curtailed energy, and curtailment percentage.[a]

	Monthly average value of produced energy (PE)	Monthly average value of curtailed energy (EC)	%
July	1,581,600.00	46,063.00	2.83
August	2,220,000.00	118,289.00	5.06
September	1,422,000.00	199,749.00	12.32
October	1,051,200.00	165,726.00	13.62
November	742,474.50	138,470.75	15.72
December	1,249,392.50	232,537.25	15.69
January	1,003,657.00	210,634.00	17.35
February	1,228,690.00	155,089.00	11.21
March	1,070,539.50	157,435.50	12.82
April	1,198,800.00	9,476.50	0.78
May	781.800.00	153,249.50	16.39
June	1,167,000.00	100,438.50	7.92
AVERAGE	1,226,429.46	140,596.50	10.28
SUM (annual)	14,717,153.50	1,687,158.00	–

[a] Data of months November 2002–June 2004 were used to form this table. Previous data were considered inadequate, because of repair works and retrofit on electromechanical equipment which took place during that period.

could be absorbed in the ES, in relevance with the total installed wind power (Fig. 5) [6]. Presented data show that W/Fs seem to appear very good operation results (high energy production with capacity factor ∼40%).

This affects the W/F's operation in a way that as it appears, during summer months higher absorption of wind energy is marked, while during winter months, when power demand is reduced in Crete, higher curtailment percentages are imposed to the W/F. It is proposed that an electrolysis unit is installed so that the curtailed percentage of the produced power could produce hydrogen, which may either be bottled and distributed to companies dealing with gases or be re-electrificated using fuel cells and supplied to the grid when necessary.

Monthly average value of produced and curtailed energy,[1] are shown at Table 2, as well as the corresponding curtailment percentage, in Fig. 6.

All above data are shown at the following Fig. 7, where it appears that during summer months higher absorption of wind energy is marked, while, during winter months, when power demand is reduced in Crete, higher curtailment percentages are imposed to the W/F.

As it is shown on Table 2, average monthly curtailment energy, is 140,596.50 kWh, and the corresponding daily[2] one is 4686.55 kWh. Consequently, the rejected power approaches 200 kW, therefore this will represent the nominal power of the electrolysis system which is to be installed.

Two scenarios of exploitation of produced hydrogen are considered; the first refers to its bottling and distribution to companies dealing with gases, and the second regards the case of its re-electrification using fuel cells and its supply to the grid when necessary. Both scenarios are taken into consideration in a feasibility study in terms of an investment in question.

Table 3
Main specifications of the electrolysis unit.

Produced hydrogen		
H_2 nominal flow	Nm^3/h	40 (4 units × 10)
Min/max H_2 flow		10/40
Min/max pressure	bar(g)	5/10
H_2 quality	%	≥(9(((
Power supply		
Voltage	VAC	3 × 400 + PE
Installed power	kVA	320
Frequency	Hz	50
Consumption		
Power (unit)	kW	168 (@ 100% load)
Power (total)	kW	192 (@ 100% load)
Water consumption	l/h	<40

4.1. H_2 production through electrolysis [7–9]

The electrolysis unit (Fig. 1) will be of type H_2 IGen® Series 1000/40/10, with a capacity factor of 70% and a specific consumption of 4.8 kWh/m^3, is characterised by the features in Table 3.

It is estimated that this unit is able to produce 28,800 m^3 on monthly basis, provided that it is continuously supplied with the average curtailed energy[3] as well as that it operates at the nominal level.

The electrolyser must be supported by several subsystems at its inlet and outlet. The most significant of them are: the water de-ionizer, the cooling unit and the H_2 de-oxo-dryer. Thus, taking into account Table 3, their features will be as follows:

Storage tank: The hydrogen produced by electrolysis flows into a conventional insulated tank. The volume of hydrogen storage tank is 15 m^3 and contains 1000 Nm^3 H_2 at 1 MPa. It is filled up to the nominal volume in 25 h (40 Nm^3/h H_2).

Compressor – bottling unit: For the specific system an oil driven piston compressor was chosen, with the following features:

Oil driven piston compressor		
Flow	Nm^3/h	35
Electrical motor	kW	11
Input/output pressure	bar	10/200

The first potential scenario, that can be applied in the frame of such investment, would be the bottling and distribution of the produced hydrogen for non-energy usage (food/plastic industry, hydrocarbon reforming). The installation of a hydrogen bottling unit and supply of storage bottles – appropriate to store and transfer the above hydrogen quantities – would be necessary.

[1] "Effected curtailment" was considered as curtailed energy (and not "commanded curtailment").

[2] All data refer to 30 days months.

[3] This fact is taken for granted, so as to simplify the studied case and the measurements.

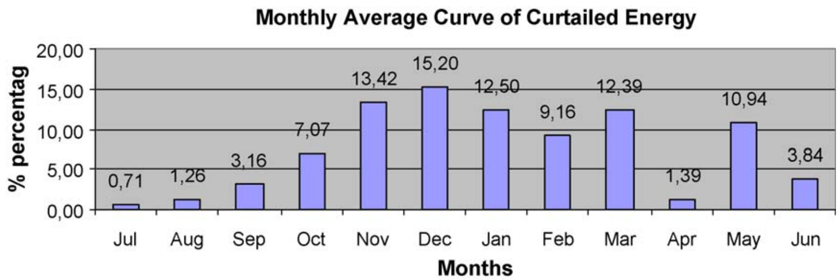

Fig. 6. Monthly average curve of curtailed energy percentage.

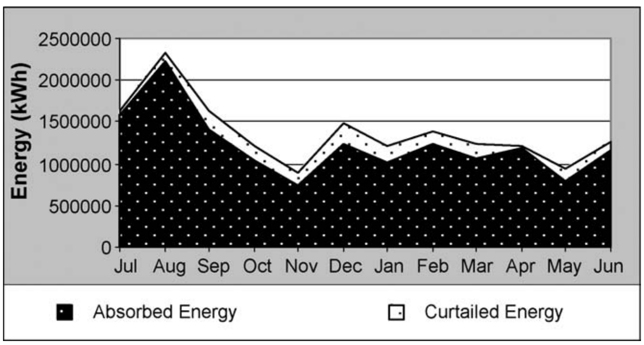

Fig. 7. Annual average energy production and curtailment curve.

Table 4
Main specifications of the peripheral units.

Water treatment unit – de-ionizer		
Water supply (outlet)	l/h	30–45
Cooling system		
Installed power	kW	1.2
De-oxo-dryer		
Installed power	kW	3×1 kW
Consumed power	kW	50% install.

The bottling unit has the following features: bottling pressure 200 bar, bottle volume 0.050 m^3, bottling capacity 8.5 Nm^3 H_2 each one. For practical and financial reasons, the W/F should be supplied with 500 such bottles so as the non-stop distribution to be insured.

Fuel cells: In case that the second scenario is adopted, taking into consideration that the monthly production of hydrogen is 28,800 m^3 as well as that the fuel cells consume 0.7 m^3 for each produced kWh, it can be inferred that the proposed fuel cell should operate with 60 kW, as nominal value, (3 units of 20 kW). The capacity factor of the above unit is 60%.

Finally, the purchase and installation of an automating intelligent switching system is necessary to assure smooth operation.

4.2. Electrolysis facility feasibility study

All the above data is included in the economic analysis, which aims to evaluate the feasibility of such an investment in pay-back time of 10 years.

The data taken into consideration for both scenarios are:

- The investment is self-funded
- Required building and land are already available
- Capital cost = 10%
- Inflation = 2%

Table 5
Costs of the feasibility study and resulting present value.

Effluxes	
Cost of electrolyte, compressor-bottling unit and peripheral units	800,000 €
Cost of storage tank	150,000 €
Cost of control and interface system	20,000 €
Cost of 500 H_2 storage bottles (a' scenario)	75,000 €
Cost of fuel cell (5,000 €/kW) (b' scenario)	300,000 €
Total cost of fixed equipment (a' scenario)	1,045,000 €
Total cost of fixed equipment (b' scenario)	1,270,000 €
Cost of water consumption/year (0.88 €/m^3, industrial invoicing, Crete)	345.5 €
Cost of annual maintenance[a]	3000 €
Total operational expenses/year (a' scenario)	2345.5 €
Total operational expenses/year (b' scenario)	3345.5 €
Influxes	
Remaining value of the main equipment	350,000 €
Annual income from the produced H_2 sales: 345,600m^3 (2 €/m^3) (a' scenario)	691,200 €
Annual income from produced energy sale (f/c, 493,714 kWh, 0.07973 €/kWh) (b' scenario)	39,364 €
After processing all above data, the resulting[b] present value is:	
P.V. (a' scenario) = 3,397,848.463 €	
P.V. (b' scenario) = −909,111.513 €	

[a] Infrastructure maintenance takes place once a year, lasts for a week, whereas it does not affect units' operation and hydrogen production, since the 4 units of the electrolyser operate in parallel.

[b] It must be noted that the resulting Present Value was estimated on a simple-version basis, using simplified calculations, comparatively to the standard approach that is followed in such cases.

- There are no surplus products from year to year
- Infrastructure life span = 20 years (apart from the peripheral units that have 10 years only life span; Table 4)
- Infrastructure value after 10 years = 1/2 of initial value
- The feasibility study is accomplished by using the method of present value

The total fund of investment, which consists of the costs of all the units in the system, are shown on Table 5.

Thus, it is obvious that in the case of curtailed energy exploitation and, in particular, when curtailed energy is used as power supply for H_2 production, for scenario 1, the whole investment is deemed feasible. On the contrary, in the second case when, the produced H_2 is used in fuel cells for electrical power production (second scenario), the results are quite different.

5. Exergy analysis [10–12]

Exergy is a term rather recent that is more and more used in the technical terminology.

Energy is neither created or destroyed. However, it is converted into a not exploitable form; kinetic energy converted in heat because of friction, for example. Consequently, we need a better

norm for the evaluation of energy quality, which represents the real possibilities of system to produce work.

Exergy is the useful energy that can be exploited from a energy resource or a material, which is subjected in an approximately reversible procedure, from a initial situation till balance with the natural environment is restored. Exergy is dependent on the relative situation of a system and its ambient conditions, as they are determined by a sum of parameters, and it can be equal with the zero (in a balanced situation with the environment).

In order to understand exergy's further significance, the following simple examples are presented:

- A system in complete balance with the environment does not contain exergy. When there are not any differences in their characteristics, a procedure cannot be accomplished.
- A system which is not in balance with its environment, includes exergy, which is also increased as long as the system declines from its ambient conditions. Thus, the hot steam has got higher exergy content during winter than summertime, unlikely regarding a piece of ice during the above seasons of year.
- When energy quality reduces, exergy is «destructed». Consequently, exergy it is the part of energy that is exploitable for the human activities and has got economic significance.

Exergy is used as a term mainly in the thermodynamics, when implicated with fluid thermal processes. Its application however can be extended in the total of energy and first materials conversions in the human activity. Exergy analysis main advantage is that it connects the real output with the theoretical (ideal) one. Even if the theoretical maximum cannot be reached, it provides a metre of comparison for the further possibilities of a procedure optimisation.

Wind energy (kinetic) when wind goes through a wind turbine's (W/T) rotor's surface (turning part) is given by:

$$\frac{1}{2}\dot{m}V^2 = \frac{1}{2}\rho AV^3 \quad (1)$$

where $\dot{m} = \rho AV$, is the air flow going through the W/T's swept area, ρ, density of air, A, rotor's surface area, V, wind speed (horizontal constituent).

Exergy of wind energy is the useful amount of energy that is taken from the wind. Maximum energy amount would be received if all the Ekin of wind was changed in electrical energy. A W/T system does not exploit all the kinetic energy of wind which runs through its blades.

W/T's energy efficiency is defined by:

$$n_{\mathrm{W/T}} = \frac{P_{\mathrm{electrical}}}{P_{\mathrm{kinetic}}} = \frac{\dot{P}_{\mathrm{out}}}{1/2\dot{m}V^2} = \frac{\dot{P}_{\mathrm{out}}}{1/2\rho AV^3} \quad (2)$$

Thus, for one W/T, the exergy output is:

$$n_{\mathrm{W/T,ex}} = \frac{E_{\mathrm{electr.}}}{E_{\mathrm{kinetic}}} = \frac{W_{\mathrm{electr.}}(\mathrm{Wh})}{P_{\mathrm{wind}} \cdot 8760\,\mathrm{h}} = \frac{W_{\mathrm{electr.}}(\mathrm{Wh})}{1/2\rho AV^3 \cdot 8760} \quad (3)$$

It is known that a W/T cannot exploit the complete power of wind. Energy efficiency of a W/T is affected by three efficiency factors:

- Cp: According to Betz law, a W/T can exploit up to 59.3% (16/27) of wind energy.
- Ng: Electric generator efficiency can approach the percentage of 90–95% or even more for inductive generators connected to the electric network.
- Nb: W/T's sub-systems efficiency factor. Frictions between the rotor turning part and the rolling bearings appear, resulting in heat production, which the cooling liquid absorbs from the gearing box, the generator and the other elements. Exergy losses appear also in electronic devices, which contribute in the smooth W/T's start and operation, and consume 1–2% of the energy. Totally, Nb can approach 95% for modern, technologically developed W/Ts.
- Finally, in the exergy output of a W/T or a wind park, we should also include the availability factor, which refers to right installation, maintenance and operation of the facility. A well-organised wind park can reach rates approximate to 95–98%, while the output efficiency is decreased, for cases of insufficient maintenance, up to the 60–70%.

Sankey diagrams can be worked out, which also show the exergy flow in a wind park. Figs. 8 and 9 represent the exergy losses of an efficient and an unefficient wind park, respectively.

As it can be seen, there is an excellent exploitation of wind energy for an organised park that operates efficiently and effectively.

Consequently, the availability factor is the most important one that defines the output of a wind park. However, the correspondent technology that is used is also important, pitch or stall control and synchronous or asynchronous generator (pitch control and asynchronous generators outrace).

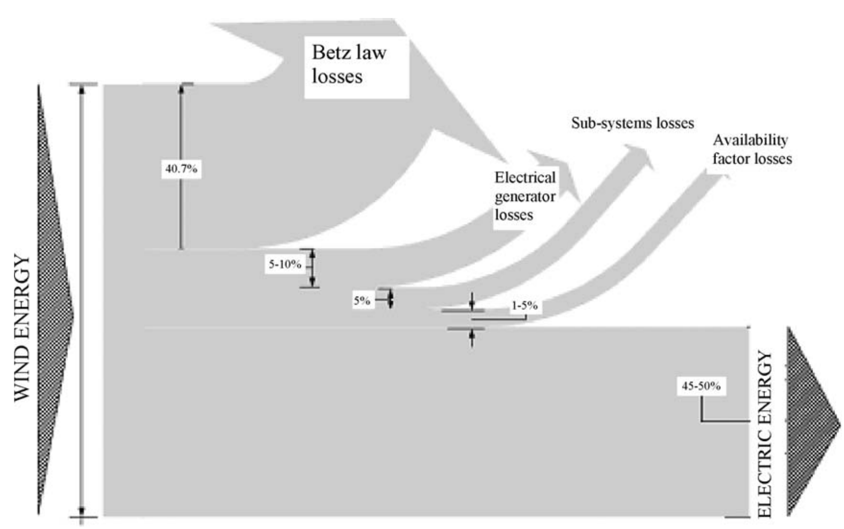

Fig. 8. Sankey diagram on an efficient wind park.

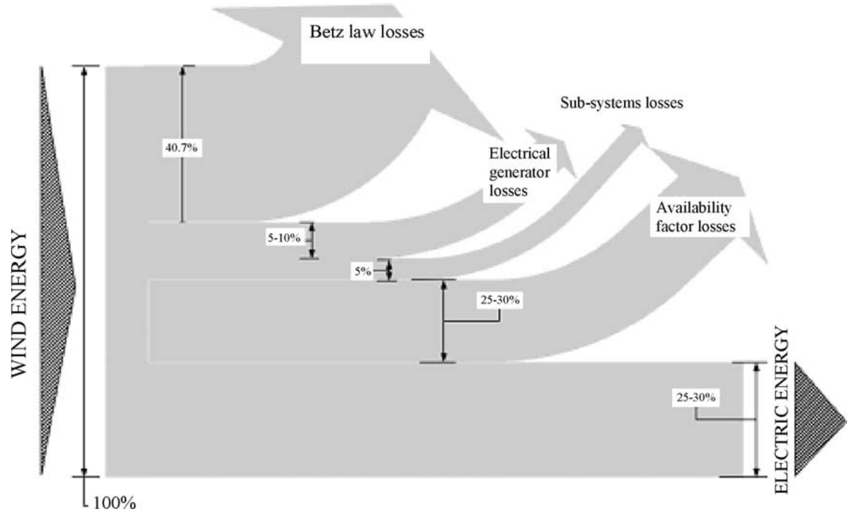

Fig. 9. Sankey Diagram on not functional wind park.

5.1. Exergy analysis of the case study

The scenario that is examined is the first scenario. In order to estimate the exergetic losses during the energy conversion and transmission to network, three cases were estimated, taking the following necessary data for calculations into account:

- the wind park consists of 9W/Ts
- air density (ρ) is considered as 1.2225 kg/m3, like on sea level.
- rotor's surface area (A) is 1256.63 m^2 (rotor blades' length, 20 m)
- wind speed (V, horizontal constituent), regards the monthly average wind speed for each one of the months September 1999–August 2005
- Electrolysis exergy efficiency is considered to be 67% [13]

In the first case (Fig. 10(1)) the whole amount of energy produced by wind turbines is converted to hydrogen. There are two kinds of losses taking place. The first one is between the wind turbines' bases and the wind farm's substation, due to line losses. The second one is due to electrolysis exergy losses (efficiency 67%).

(1)

1st scenario: Total produced power supplied to electrolysis unit

	actual produced power by turbines	LOSSES Turbines→ Windfarm	E recorded by O&M	LOSSES Windfarm → Electrolysis	E bounded in produced H2	Total Exergy Efficiency(1)
SEPT.	1.040.645	1,30%	1.061.649	33,00%	711.305	66,13%
OCT.	1.308.792	0,67%	1.316.147	33,00%	881.819	66,55%
NOV.	1.096.696	1,88%	1.109.296	33,00%	743.228	65,74%
DEC.	1.515.569	3,78%	1.466.821	33,00%	982.770	64,47%
JAN.	1.330.799	4,11%	1.282.034	33,00%	858.963	64,24%
FEB.	1.228.176	0,88%	1.280.703	33,00%	858.071	66,41%
MAR.	1.140.774	6,06%	1.056.155	33,00%	707.624	62,94%
APR.	912.483	2,37%	918.708	33,00%	615.535	65,42%
MAY	1.023.434	5,89%	987.044	33,00%	661.320	63,05%
JUN.	1.336.667	6,41%	1.262.046	33,00%	845.571	62,70%
JUL.	1.592.958	3,50%	1.569.753	33,00%	1.051.735	64,65%
AUG.	1.615.285	2,60%	1.633.622	33,00%	1.094.527	65,26%
Average		3,29%		33,00%		64,80%

(2)

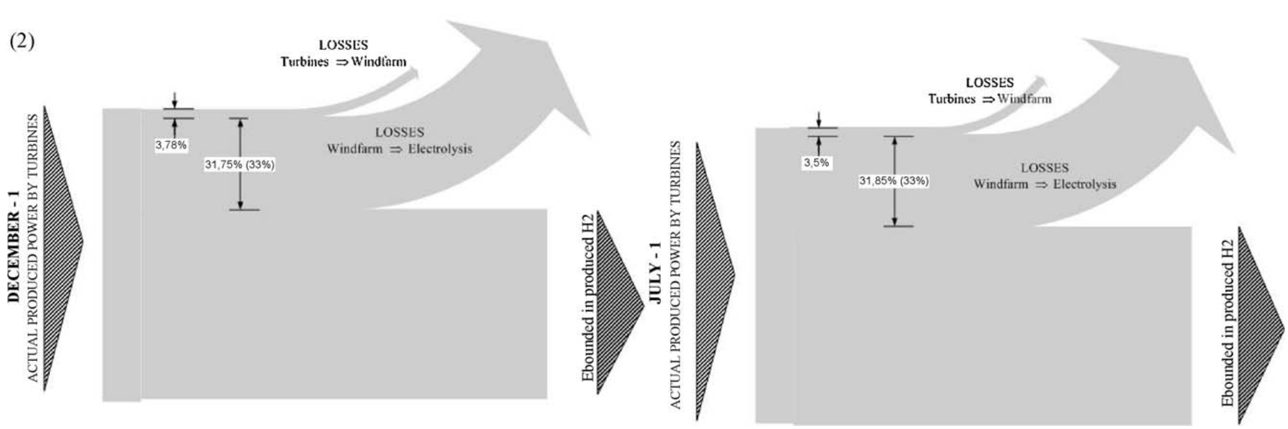

Fig. 10. (1) Scenario #1 table. (2) Sankey diagrams presenting exergy losses through the "first scenario" energy conversion system, for December and July.

(1)

2nd scenario: Curtailed power is rejected							
	actual produced power by turbines	LOSSES Turbines→ Windfarm	E recorded by O&M	LOSSES Windfarm → PPC substation	LOSSES Windfarm → PPC substation	E recorded by PPC at SS	Total Exergy Efficiency(1)
SEPT.	1.040.645	1,30%	1.061.649	3,16%	1,48%	1.011.523	94,73%
OCT.	1.308.792	0,67%	1.316.147	7,01%	0,67%	1.214.097	92,05%
NOV.	1.096.696	1,88%	1.109.296	13,25%	1,73%	937.760	83,60%
DEC.	1.515.569	3,78%	1.466.821	15,05%	1,14%	1.226.895	80,87%
JAN.	1.330.799	4,11%	1.282.034	12,33%	1,94%	1.109.236	82,77%
FEB.	1.228.176	0,88%	1.280.703	9,04%	1,47%	1.146.223	88,83%
MAR.	1.140.774	6,06%	1.056.155	12,14%	1,11%	918.216	81,62%
APR.	912.483	2,37%	918.708	1,38%	1,23%	897.435	95,10%
MAY	1.023.434	5,89%	987.044	10,83%	1,22%	871.052	83,30%
JUN.	1.336.667	6,41%	1.262.046	3,17%	1,20%	1.207.681	89,56%
JUL.	1.592.958	3,50%	1.569.753	0,70%	1,30%	1.538.100	94,63%
AUG.	1.615.285	2,60%	1.633.622	1,25%	1,28%	1.587.616	94,95%
Average		1,56%		3,12%	1,78%		88,50%

(2)

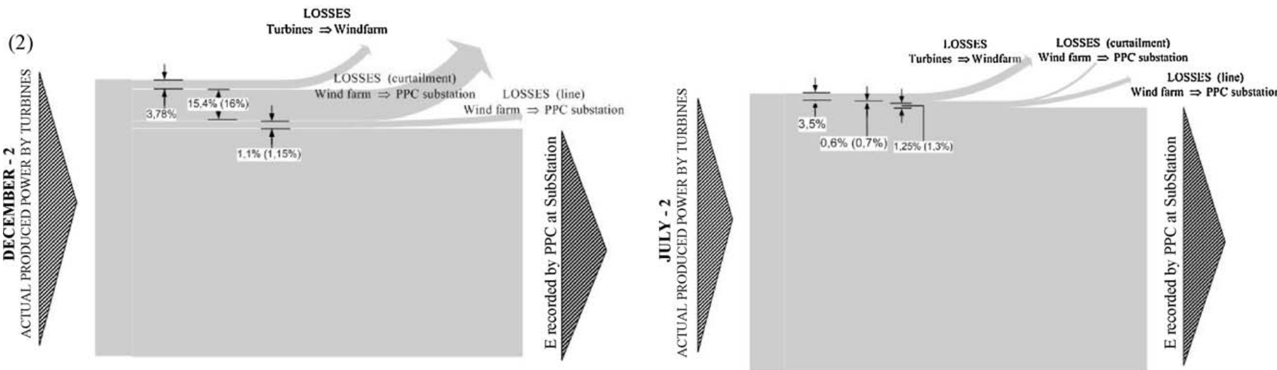

Fig. 11. (1) Scenario #2 table. (2) Sankey diagrams presenting exergy losses through the "second scenario" energy conversion system, for December and July.

(1)

3rd scenario: Curtailed power supplied to electrolysis unit										
	actual produced power by turbines	LOSSES Turbines→ Windfarm	E recorded by O&M	flow 1	LOSSES Windfarm→ PPC substation (Line)	E recorded by PPC at SS	flow 2 (Curtailment)	LOSSES Windfarm→ Electrolysis	E bounded in produced H2	Total Exergy Efficiency(1)
SEPT.	1.040.645	1,30%	1.061.649	1.013.655,5	1,48%	1.011.523	47.993,7	33,00%	32.156	96,97%
OCT.	1.308.792	0,67%	1.316.147	1.217.744,8	0,67%	1.214.097	98.402,18	33,00%	65.929	96,57%
NOV.	1.096.696	1,88%	1.109.296	956.241,5	1,73%	937.760	153.054,47	33,00%	102.546	91,83%
DEC.	1.515.569	3,78%	1.466.821	1.241.024,2	1,14%	1.226.895	225.796,67	33,00%	151.284	90,37%
JAN.	1.330.799	4,11%	1.282.034	1.125.997,2	1,94%	1.109.236	156.036,69	33,00%	104.545	90,76%
FEB.	1.228.176	0,88%	1.280.703	1.164.488,7	1,47%	1.146.223	116.214,50	33,00%	77.864	94,51%
MAR.	1.140.774	6,06%	1.056.155	928.563,8	1,11%	918.216	127.590,70	33,00%	85.486	89,34%
APR.	912.483	2,37%	918.708	907.767,8	1,23%	897.435	10.940,48	33,00%	7.330	96,11%
MAY	1.023.434	5,89%	987.044	882.514,0	1,22%	871.052	104.530,31	33,00%	70.035	89,62%
JUN.	1.336.667	6,41%	1.262.046	1.222.354,5	1,20%	1.207.681	39.691,69	33,00%	26.593	91,51%
JUL.	1.592.958	3,50%	1.569.753	1.558.461,8	1,30%	1.538.100	11.291,19	33,00%	7.565	94,99%
AUG.	1.615.285	2,60%	1.633.622	1.608.481,7	1,28%	1.587.616	25.140,71	33,00%	16.844	95,60%
Average		1,56%			1,31%			33,00%		93,18%

(2)

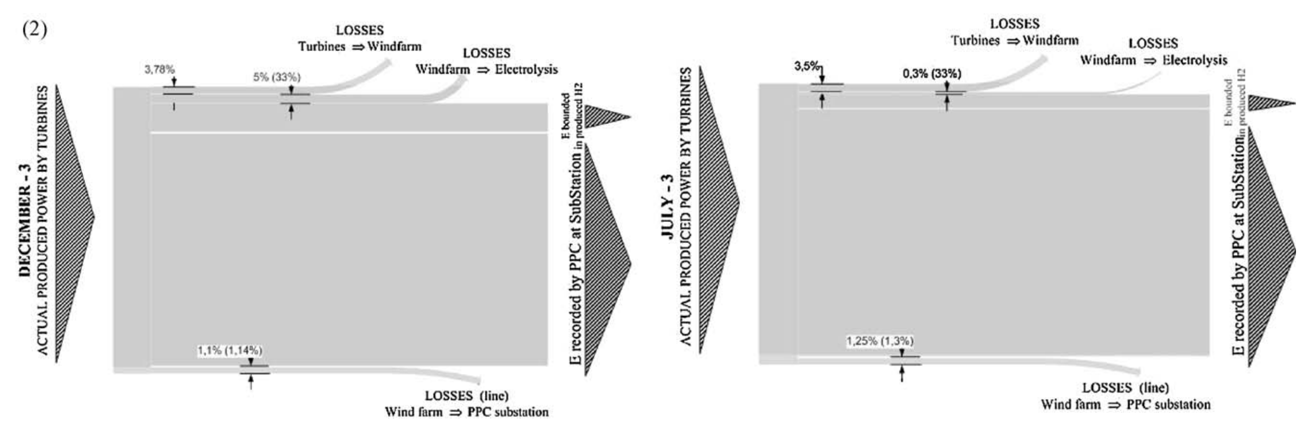

Fig. 12. .(1) Scenario #3 table. (2) Sankey diagrams presenting exergy losses through the "third scenario" energy conversion system, for December and July.

It is shown that a monthly average of exergy efficiencies during 6 years' operation (September 1999–August 2005) reaches a percentage of 64.8%. A graphical representation of this data will lead to the Sankey diagram shown on Fig. 10(2). December and July were selected as particular cases for the diagrams, because that is when maximum and minimum curtailment percentages take place, respectively.

In the second case (Fig. 11(1)), the PPC does not absorb the whole amount of produced energy because the power demand is low. In this case a serious energy percentage is lost, resulting in a reduced exergy efficiency, mostly during winter months. The three kinds of power losses taking place here are: between the wind turbines' bases and the wind farm's substation, and secondly, due to the effected curtailment and thirdly because of the line losses between W/F's substation and PPC substation, which lies several kilometres southern of the W/F. In this scenario the resulted monthly average of exergy efficiency reaches 88.5%. The use of Sankey diagram representation leads to Fig. 11(2).

The third case includes both cases 1 and 2, with the only difference that the electrolysis unit is supplied by the curtailed amount of energy. In this case all above mentioned losses take place, in different spots this time, as it is shown on Fig. 12(1). It is evident that in this case the total exergy efficiency across the energy conversion line is the greater of all (~93.2%), and this happens because a higher amount of energy is exploited. The representative Sankey diagram is shown on Fig. 12(2).

6. Conclusions

Over the last years, wind power has established itself as an economic grid-connected electricity generating technology, but its use in stand-alone power systems has been limited. This is due to many problems which still need to be solved, as well as the lack of suitable and economically viable energy storage technology. Hydrogen produced via water electrolysis could be such storage medium in the near future, especially in isolated remote areas, where the cost of electricity is high. A number of demonstration wind electrolysis units have already been installed and operate with success, proving that when capital cost is reduced, this technology will spread rapidly. The implementation of this target will significantly promote wind energy participation in the energy balance, with important profits for the national economies [14].

The wind-hydrogen technology, although at present represents a non-favourable investment, is expected that, with the reduction of equipment costs, it will also be commercially usable. The economical impact that results from the above technology, should be carefully taken into account, mainly regarding the benefits offered to a country:

- It contributes in reducing imported fuels and in the consequent financial benefits, especially for the energy isolated Greek islands.
- It accelerates the decrease in air emissions.
- It allows a major exploitation of RES, since it represents the most appropriate means of energy storage, minimizing simultaneously the curtailed surplus energy.
- It helps in restricting the scale up of the electricity grid, if hydrogen generation plants are installed in areas with a high wind power concentration and it offsets the drop of wind energy value at high penetration levels.
- It smoothes the power output and hence facilitates a more efficient operation of the electric system. The smaller scale of the fluctuations reduces the need for ancillary services to maintain power quality.
- Its use in zero-emissions fuel-cell vehicles contributes decisively in the drastic reduction of urban pollution, responsible for important resultant external costs, and finally,
- with its wide usage expansion, it decreases the necessity of conventional fuel imports, it creates new jobs and it helps the development of an indigenous technology and industry.

With the development of technology, the increase in the systems' capacity factor and, mainly, the further reduction of equipment costs, it is sure that, in the near future, hydrogen technology in combination with wind energy will be dealt more seriously by the investors, since it will be able to compete with the already existing, conventional energy producing and operating units. All the above prove that the need of the determination of a national strategy for exploitation of wind energy in combination with hydrogen is urgent.

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